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*Author(s):* Scott DeMuth (LANL)
Mitsutoshi Suzuki (JAEA)

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# Proliferation Risk Assessment for Large Reprocessing Facilities with Simulation and Modeling

Mitsutoshi Suzuki[1] and Scott Demuth[2]
[1]*Japan Atomic Energy Agency, 2-4 Shirakata, Tokai, Naka, Ibaraki 319-1195 Japan*
*Tel: +81-29-284-3475, Fax: +81-29-284-3678, E-mail: suzuki.mitsutoshi@jaea.go.jp*
[2] *Los Alamos National Laboratory, Los Alamos, NM 87545-0001 USA*
*Tel: +1-505-667-2180, Fax: +1-505-665-5125, E-mail: sdemuth@lanl.gov*

**Abstract** - *Proliferation risk assessment has been investigated to develop a performance-based approach in which the likelihood of diversion incidence, as well as the uncertainty of nuclear material accounting, is simultaneously considered to install intrinsic and extrinsic countermeasures in a conceptual design of a future reprocessing facility. A simulation and modeling approach has been applied to evaluate safeguards performance in a facility-level and diversion pathway analysis, which is demonstrated to detect more efficiently a small and protracted diversion that is usually investigated by trend analysis. Although an incidence probability of diversion is difficult to estimate because of its intentional act, the Markov model methodology originally developed by the proliferation resistance and physical protection working group in the generation IV international forum is incorporated into two-dimensional probability distribution. In a comparative study, a hypothetical reprocessing process for light water reactors and fast breeder reactors are modeled and investigated using the distribution that is derived from an inherent nature in the deterministic International Atomic Energy Agency safeguards criteria. By comparison with conventional diversion scenarios, which are abrupt and protracted loss, and verification measures to conform to the criteria, the diversion path analysis with a simulation and modeling tool is valuable to pursue a risk-oriented performance in safeguards. This simulation and modeling approach has already been carried out in the United States to investigate safeguards performance in future reprocessing processes, and we have been collaborating on the development of safeguards simulation tool to enhance the safeguards by design approach.*

## I. INTRODUCTION

In the past few decades, optimizing the tradeoff objectives, that is safe and timely detection of diversion of special nuclear material (SNM) in the International Atomic Energy Agency (IAEA) safeguards, in a theoretical manner, using a sequential statistical approach for material unaccounted for (MUF) in nearly-real-time accounting (NRTA) without knowing the distribution of loss beforehand and enhancing game theoretical approach with assuming payoff parameters have been developed and successfully applied to the IAEA safeguards evaluation in reprocessing facilities.[1)] Recently, to develop an advanced safeguards approach for a pyro-processing facility and to provide full operation of the Rokkasho Reprocessing Plant (RRP), an explanation of the tradeoff objectives was required to reconstruct an international consensus about, as well as to maintain credibility with, the accounting-based IAEA safeguards criteria at a facility level. However, because of a large throughput of nuclear material in a short operational period and the harsh environment to measure plutonium in a molten salt, it has become difficult to ensure that no diversion occurs while relying solely on accounting data.

On the other hand, to pursue more cost-effective and efficient regulatory methodology, even in a severe accident, a risk-informed approach has been introduced into safety in the past few decades. Because of the inherent nature of an intentional act in security and safeguards, an introduction of the risk notion is not so straightforward; particularly in safeguards, the adequacy of risk has not been internationally discussed so far.[2)] For instance, a Gaussian assumption for the likelihood of misuse and/or diversion is too idealistic in the definition of probability, and a quantitative formalization for initiation of the incidence in security and safeguards has been fairly controversial.

In addition, a simulation and modeling (S&M) study has been given much attention in current nuclear research and development (R&D) activities based on the excellent advancement of its industrial use and computer capability.[3] Advantages of the S&M approach in creating an evaluation tool to estimate safeguards performance are to provide a numerical platform and construct a safeguards envelope for possible proliferation scenarios and to verify enough detection probability using a feasible process model to make an accurate representation of the process variation.

From an inspector's point of view, it is not simple to ensure that no possibility exists to misuse and/or divert SNM because any system would have diversion pathways that can defeat containment and surveillance. However, the S&M approach using a Markov Monte-Carlo method as well as a risk-based diversion path analysis would be a modern approach that is popular as in the other nuclear science fields.

In this paper, we will discuss the possibility of applying the risk-informed approach to designing work in a safeguards system and will present preliminary studies of a proliferation-resistant system to be used in a future reprocessing facility.

## II. RISK-INFORMED SBD

An incorporation of the safeguards by design (SBD) approach into the conceptual design and system development phase increases regulatory effectiveness, as well as operational readiness, and also reduces expensive and time-consuming retrofitting. Risk-informed and performance-based approaches have been pursued to develop a modern evaluation methodology for regulatory authorities instead of a prescriptive and deterministic one, and according to the degree of the evaluated risk, a limited resource should be assigned to provide for a potential accident and incidence. Compared with a probabilistic safety assessment (PSA) in safety, an inherent difficulty to predict the incidence probability induced by malicious and intentional acts has been pointed out.

It would be difficult to estimate an incidence frequency, but a risk-oriented resource allotment in countermeasures to provide for the security and safeguards risk is highly reasonable. In the current IAEA safeguards approach, the risk notion has already been taken into consideration as a state-level evaluation, and a safeguards inspection has been carried out according to a risk analysis with a possible diversion scenario. However, the advantage of using a mathematical formalization of a proliferation risk probability could be demonstrated in an objective manner, and the quantitative representation and estimation is indispensable in the SBD approach. Therefore, we have introduced the Markov model into the proliferation risk analysis developed by the Generation IV's proliferation resistance and physical protection working group (PR&PP WG) to describe the incidence risk.[4]

In this model, whenever a significant quantity (SQ) of nuclear material is processed, an incidence chance for diversion and/or misuse is assumed to be exposed. For discussion here, we ignore the loss/diversion risk due to plutonium inventory. The frequency of processing an SQ forms an incidence probability, and the stochastic events sequence is governed by this time interval. The interval is defined by both the SQ processing time and various safeguards measures' implementation so that the incidence frequency can be expressed with a Poisson probability distribution. The Markov model has been broadly accepted in proliferation risk assessment led by the PR&PP WG. It has not yet been applied to classical safeguards because proliferation risk assessment (PRA) has not yet become a quantitative safeguards component. However, the measurement error probability distribution used in conventional safeguards could be considered in conjunction with the Markov process. This two-dimensional probability includes both incidente and measurement error probabilities, which would be a unique feature of safeguards for assessing proliferation risk, as shown in Fig. 1.

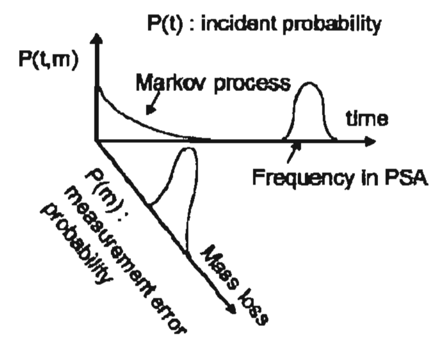


**Fig. 1 Two-dimensional probability for safeguards**

PSA has been discussed only in the incident probability dimension because the measurement error threshold has never been exceeded in normal operation. However, the safeguards threshold comes very close to normal conditions in future large throughput facilities, so the measurement error probability should be considered simultaneously as two dimensional.

## III. PROCESS MONITORING (PM) IN

NEXT-GENERATION SAFEGUARD INITIATIVE[5,6]

The main goal of nuclear material accountancy (NMA) is to confirm within measurement uncertainty that a significant quantity of SNM has not been diverted within the inventory period. Because the NMA measurement uncertainty increases as the facility throughput increases, despite significant efforts through the years to reduce this measurement uncertainty it remains difficult to satisfy the IAEA accountancy goal for large throughput facilities. PM can be used as an additional measure to NMA by either direct or indirect confirmation of selected inventory measurements or by confirmation of data consistency. Used for data consistency, PM can provide additional assurance that a facility is being operated as declared by verification of selected operating procedures.

The United States (US) National Nuclear Security Administration (NNSA) has initiated a PM project through its Next-Generation Safeguards Initiative (NGSI) to demonstrate the added value of safeguarding a nuclear facility with PM, in addition to NMA alone. In the near term, the analysis tools being developed by this project could be used to identify existing process control data in operating reprocessing facilities not currently shared with the IAEA that could significantly enhance current PM efforts. In the long term, the analysis tools being developed by this task could be used to identify new process control instrumentation and/or new independent IAEA instrumentation to be used for advanced PM in new facilities. Both enhanced and advanced PM could reduce the time required for inspectors to evaluate process monitoring measurements through new data analysis techniques.

1. Methodology for Quantitatively Combining NMA and PM

The following example is used to demonstrate how NMA and PM detection can be quantitatively combined. The IAEA NMA goal for interim inventory is the detection of an SQ of SNM (e.g., 8 kg of plutonium) within 30 days with high confidence. Based on the estimated NMA performance for a hypothetical 800 metric tons heavy metal (MTHM)/year reprocessing facility, 3.3 × Sigma-MUF is ~11.5 kg of plutonium at 30 days of inventory. Sigma-MUF represents the cumulative measurement error for NMA over the entire inventory period at one standard deviation. The 3.3 × Sigma-MUF represents 95% confidence as determined for NMA applications where the concern is only loss, not gain (e.g., one-sided normal distribution). It can be estimated that at 30-days inventory, 8 kg of plutonium can be detected at ~2.3 × Sigma-MUF, which is equivalent to ~74% confidence for a one-sided normal distribution. As an example to demonstrate combining NMA and PM detection probabilities, assume that for the same 800 MTHM/year reprocessing facility, given a specific diversion path, it has been determined that with PM the loss of 8 kg of plutonium within 30-days can be detected with 65% confidence. If we assume that instrumentation for NMA and PM are independent, and if NMA and PM both fail to detect diversion, then the overall probability of failure is derived as a convolution of failure of NMA and PM. This result indicates that for the diversion scenario of interest and a 30-day interim inventory, 8 kg of plutonium loss can be detected within 74% confidence with NMA alone and 91% (=1-(1-0.74) × (1-0.65)) confidence with NMA plus PM. Thus, for this example, combined NMA plus PM nearly satisfies the IAEA NMA interim inventory goal for detection of diversion of a significant quantity of SNM at high confidence (95%), whereas NMA alone falls significantly short at 74%.

2. NGSI PM Project Components

As stated in the previous section, one of the objectives of the NGSI PM project is to demonstrate the added value for safeguarding a spent fuel reprocessing facility with PM, in addition to NMA alone.

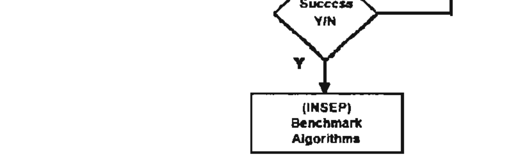


**Fig. 2 Components of NGSI PM Methods**

Additionally, through this effort to demonstrate added value, it is expected that the required methodology being developed will also be directly useful for the safeguards design of nuclear facilities. The methodology being developed is composed of many distinct tasks, as shown in Fig. 2. The Diversion Detection Algorithm (DDA), with its associated quantitative assessment of the contribution to safeguards by PM, is the foundation of the

NGSI methodology. The other tasks shown in Fig. 2 either allow the demonstration of the DDA or are used to verify the correctness of the DDA, with the exception of advanced instrumentation development. The advanced instrumentation task is essentially performed in parallel with the other tasks but then is aligned with actual facility needs by optimization with the DDA.

Recent joint discussions between the US and Japan Atomic Energy Agency (JAEA) related to the International Nuclear Safeguards Engagement Program (INSEP) have identified a safeguards topic for joint collaboration, "Benchmarking Process Monitoring Models for Reprocessing in support of Joint Safeguards Modeling & Simulation." Plans are being made for the independent development of PM models by the US and JAEA to avoid conflicts due to export control and intellectual property issues. Identical diversion scenarios will be evaluated for detectability with US and Japanese PM models. The use of actual data will be minimal, if any, to avoid proprietary information concerns. Benchmarking will be used in a fashion similar to that done by the US Nuclear Regulatory Commission (NRC) for thermal-hydraulic codes, where actual reactor loss-of-coolant data are limited and therefore the results of independent codes based on synthetic scenarios are compared (i.e., benchmarked) for validation.

## IV. CASE STUDY WITH LWR & FBR REPROCESSING MODEL

A large throughput reprocessing facility is economically competitive as a modern commercial plant, and a scale of the facility reaches 800 and/or 1500 MTHM/year for the reprocessing of spent fuels from light water reactors (LWRs). As increasing the throughput in an operational period, an allowable Sigma-MUF in NMA defined in the IAEA safeguards criteria must be controlled to ensure that no diversion and/or misuse of SNM occurs. However, with the large throughput, the Sigma-MUF would likely exceed the criteria because of the accumulated measurement error, and even the timeliness goal could not be attained when an indication of diversion and/misuse must be detected within a 30-days in plutonium. In this case study, the typical plutonium-uranium reduction extraction (PUREX) process as the reprocessing of LWR spent fuels and the new extraction system for trans-uranium (TRU) recovery (NEXT) process as an advanced fast breeder reactor (FBR) reprocessing process[7] are considered, respectively.

In Figure 3(a), the typical PUREX process is shown and is composed of the first and second plutonium purification process, with several series of pulse columns used to increase quality of the plutonium product.

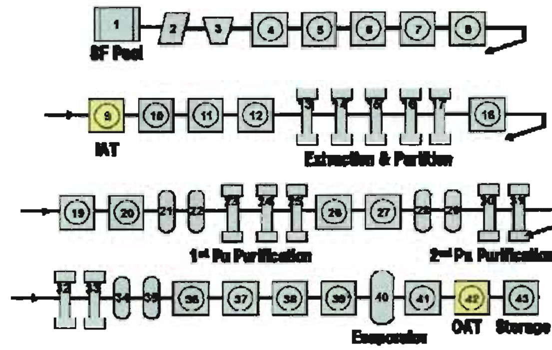


Fig. 3(a) PUREX process for LWR reprocessing

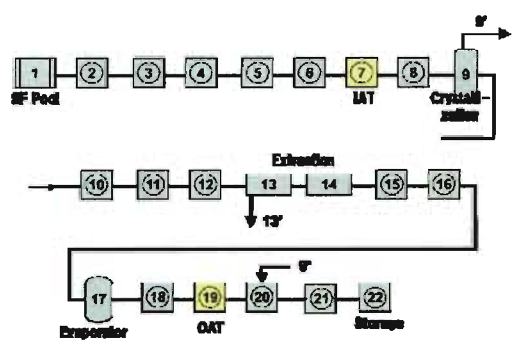


Fig. 3(b) NEXT process for FBR reprocessing

As shown in Fig. 3(b), innovative process instruments, such as the crystallization process and effective centrifugal extractors, are installed to pursue the highly efficient and proliferation-resistant process. In crystallization, most of the uranium is recovered from the dissolution using a solidification mechanism with a temperature controlled below the coagulation point, and a ratio between plutonium and uranium in the remaining solvent after the crystallization is roughly adjusted to the same ratio as the loading fuel manufactured from the product. After crystallization, two-series centrifugal contractors equipped with compactness, high throughput, and small hold-up volume produce the product. The purification level of the product, which is a mixture of plutonium and uranium, is not enough compared with using the PUREX process, but the low-decontaminated product is used with raw material for the next FBR fresh fuel. The plutonium-uranium mixture content and low-decontaminated product increase proliferation resistance.

The characteristic numbers of the LWR and FBR reprocessing process are presented in Table. 1. The total plutonium throughput of FBR is about 2.5 times higher than that of LWR because of the differences of the initial fuel composition.

Table 1. Characteristic numbers of LWR and FBR reprocessing models

| Reprocessing model for | LWR | FBR |
|---|---|---|
| Throughput (t/year) | 800 | 200 |
| (tPu/year) | 7 | 18 |
| (t/day) | 4 | 1 |
| Input (batch/day) | 1b/1.25d | 1b/0.62d |
| (kgPu/batch) | 52 | 55 |
| (gPu/l) | 2.75 | 50 |
| (gU/l) | 250 | 450 |
| Product (batch/day) | 1b/5d | 1b/4d |
| (kgPu/batch) | 210 | 24 |
| (gPu/l) | 250 | 92 |
| Inventory (kgPu) | 315 - 480 | 130 - 180 |
| Working days | 200 | 200 |

To adjust the input fuel composition for the succeeding fuel fabrication in the NEXT process, the plutonium product concentration is managed to satisfy the specification in the FBR fuel. Therefore, the plutonium concentration in the FBR is about 18 times higher than that in LWR. Moreover, the in-line process inventory of the FBR is about 40% less than that of the LWR with adopting compact inventory instruments, as well as the compromise of an operational redundancy.

1. Sigma-MUF and Inventory

To investigate the NMA performance of both processes, a conventional NMA simulation code named as the safeguards approach system for nuclear fuel cycle evaluation (SANFCE)[3)] is used. The SANFCE is a comprehensive evaluation system for the material control and accounting (MC&A) design and effectiveness of nuclear fuel cycle facilities that was developed during the 1990s at the Japan Atomic Energy Research Institute (JAERI), one of the former organizations of JAEA. This system is designed to model simulated flow and inventories of all declared nuclear materials for reprocessing, plutonium conversion, and mixed oxide (MOX) fuel fabrication plants. The MUF of the material balance area (MBA) and material balance period (MBP) for NRTA is calculated to determine a variance and co-variance matrix for several statistical tests with sequential material balance data. As described in Table 1, the inventory in the FBR reprocessing is far less than that of the LWR, although the plutonium throughput of the FBR reprocessing is almost two times larger than that of the LWR. Using the SANFCE code, the Sigma-MUF is calculated to investigate typical NMA characteristics of both reprocessing processes. The contribution of the individual measurement error on the total measurement variance is expressed as a ratio to the total variance, as shown in Table 2.

Table 2 Individual contribution on the measurement error variance of the input, output, and inventory at LWR and FBR reprocessing process

| | | Input | Output | Inventory | Total |
|---|---|---|---|---|---|
| LWR (/ σMUF-LWR) | Bulk | 7.4 | 10.8 | 3.2 | 24.6 |
| | Sampling | 26.5 | 27 | 0.5 | 54.5 |
| | Analysis | 9.9 | 6.4 | 2.3 | 20.9 |
| LWR : measured weight (kgPu) | | 1250.7 | 1237.9 | 464.6 | |
| FBR (/ σMUF-FBR) | Bulk | 3.3 | 1.6 | 2.5 | 9.9 |
| | Sampling | 0.8 | 0.3 | 0.8 | 2.6 |
| | Analysis | 2.3 | 1.3 | 41.9 | 87.4 |
| FBR : measured weight (kgPu) | | 2678.4 | 2652.9 | 180.6 | |

As shown in Table 2, the measurement error contribution of sampling at the input in the LWR and that of analysis at the inventory in the FBR play essential roles in the total Sigma-MUF. The Sigma-MUF variation is shown as a function of MBP in Fig. 4. In the error contribution in Table 2, the random and systematic measurement error for the individual measurement, such as the bulk measurement with electric manometer, the sampling measurement with circulation and the automatic sampling machine, and analysis with isotope dilution mass spectrometry (IDMS) and hybrid K-edge densitometry (HKED), is assumed to be international target values (ITV) of 2000.

As pointed out in Table 1, the in-process inventory of the LWR is larger than that of the FBR. Therefore, the measured uncertainty of the plutonium inventory of the LWR is larger than that of the FBR. On the contrary, the measured uncertainty of throughput of the LWR is smaller than that of the FBR shown in Table 2. In spite of the opposite relation between the inventory's uncertainty and the throughput's, the measurement error of the analysis for inventory in the FBR plays a main role in the total Sigma-MUF variance at a 30-day MBP. This large error in the analysis results from an element analysis at the evaporator because the relative random measurement error is assumed to be 10%.

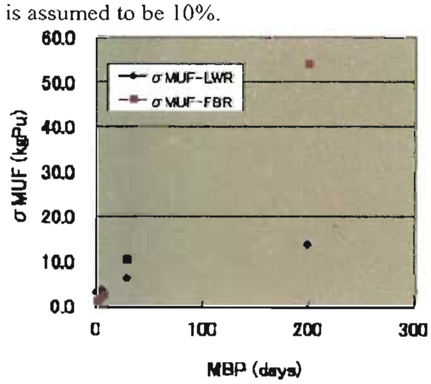


Fig. 4 The MUF variance (Sigma-MUF) change according to the MBP

Moreover, the inventory in the evaporator is not so small as to neglect its contribution to the total Sigma-MUF. As shown in the Fig. 4, the Sigma-MUF changes almost linearly according to the increase in the MBP. The Sigma-MUF of the LWR and FBR is 13.7 kg and 53.9 kg of plutonium in a 200-day MBP, respectively. According to the increase in the MBP, the Sigma-MUF gradually increases, and the large throughput in the FBR process results in the large Sigma-MUF naturally.

In terms of the PM application, the solution monitoring management system (SMMS) is the most realistic system that has already been installed into the RRP. A detection capability of diverted solution with SMMS depends on an accuracy of solution level measurement determined by the dip tube in the SMMS. The level measurement in a small volume is easier to make than that in a large volume, so a ratio of the plutonium holdup divided by the volume is a clear indicator for a performance of the detection capability of SMMS. In Fig. 5, the plutonium holdup, average plutonium mass flow rate, and volume of the vessels are shown in each step in the FBR process. The ratio in the FBR process is very similar in that it does not depend on the upstream and the downstream of the extraction, so the sensitivity in the entire process steps needs to be checked to investigate the SMMS performance.

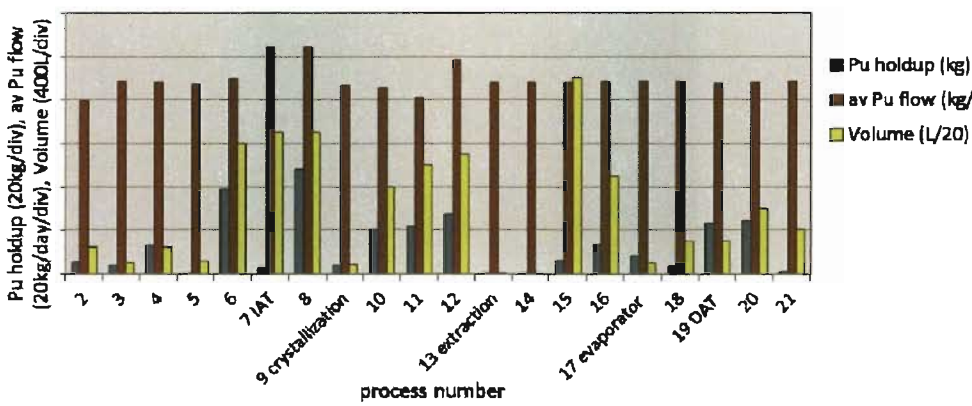


Fig. 5 Pu Inventory in the FBR process

Therefore, the high-throughput, as well as the small in-line process inventory, is a basic idea for the future reprocessing design in terms of NMA. However, it should be noted that this direction would decrease an operational margin, and a safety requirement to avoid any critical accident due to incorrect operation of the instruments must be considered. In future research, this tradeoff relation will be considered to pursue an optimum in safety, security, and safeguards (3S) by design.

These large Sigma-MUF values should require more frequent inventory verification than a 30-days interim inventory verification (IIV). However, the total inventory in the entire process should be designed to be small to decrease the Sigma-MUF in spite of the large throughput plutonium amount (18 tons of plutonium per year), so that a possible improvement of measurement techniques and an application of PM would make this plant meet modified safeguards criteria that are based on detection probabilities of specified misuse scenarios.

2. Proliferation Risk Assessment (PRA)

As mentioned in Section II, the mass balance, as well as the incidence time, plays an important role in evaluating the two-dimensional risk probability. To calculate the incident probability, we use a Markov model[8], as shown in Fig. 6. In addition to physical inventory verification (PIV) and IIV in the IAEA safeguards, monitoring of SMMS signals is considered to be an additional measure, as well as the extrinsic barrier in this model. The individual time interval of the safeguards measures in the entire process described as $T_D$ in Fig. 6 is assumed to be the frequency of the incidence of diversion and/or detection at each process. The confidence level of the safeguards measure, shown as $C_D$, is defined according to the detection capability of the measure. Moreover, to consider the intrinsic barrier in the system, the time factors $a$ are specified considering material types at each process. This random stochastic process is modeled as a Poisson probability distribution.

Intrinsic barriers to misuse, such as radiation exposure and heat generation from fission products (FPs) and minor actinide (MA) components, americium and curium, must be overcome to move forward to weapon production from a diverter's point of view.

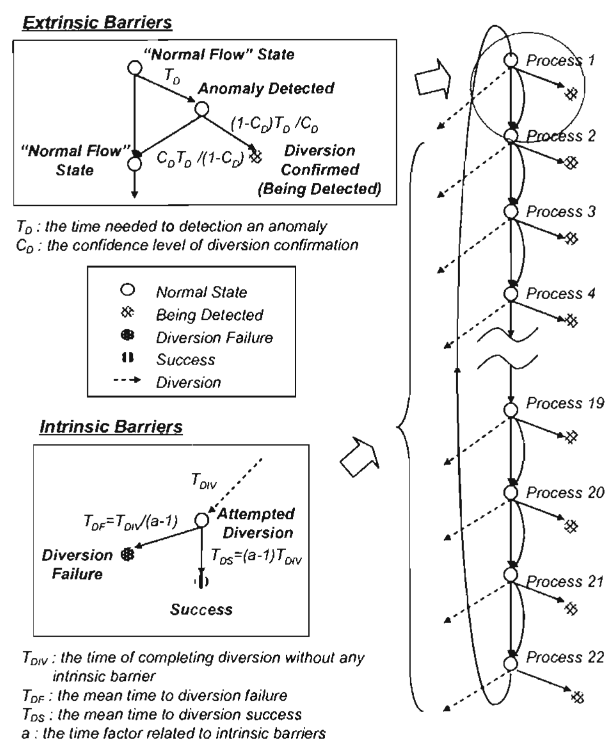


Fig. 6 Markov model for the FBR process

However, no matter how many FPs and MA components remain in the product solution, the diverter could remove these radioactive materials using some radiation protections, chemical reactions, and separation facilities. Therefore, the prolonged time, resulted in the time factor, to prepare an additional process and/or countermeasures to extract from radioactive solution to fissile material for weapon production represents a technical difficulty at each process, according to the number of FPs and MA components. Using this model and parameters, the detection and failure probabilities at each process are calculated and shown in Fig. 7.

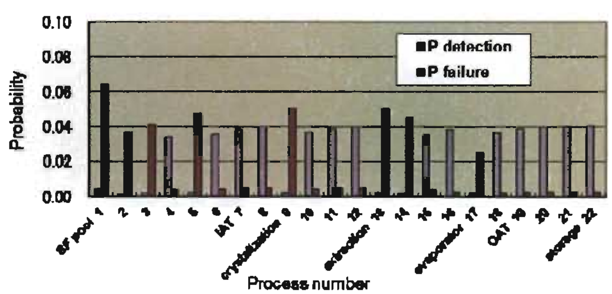


Fig 7 Detection and failure probabilities at each process

It should be noted that the SMMS is not installed into the continuous mode (CM) processes, such as dissolution 1, 2, 3, and 5, crystallization 9, extraction 13 and 14, and evaporator 17, and the low detection probabilities are compensated for by failure probabilities and lead to small success probabilities that are not shown in Fig. 7. After evaporation, the failure probability is relatively small because of the high plutonium concentration, and the high detection capability with SMMS is necessary to protect plutonium because of the low-decontaminated plutonium-uranium-mixed solution and low intrinsic barrier. The solution volume in tanks located upstream or downstream of several CM processes are relatively large to provide a operational margin, whereas the plutonium holdup in some equipment, such as crystallization, extraction, and evaporator, is designed to be very small. It should be noted that the plutonium holdup can be estimated from the level, density, and temperature (LDT) tank data from the SMMS.

## 3. Quantitative Solution Monitoring

According to the vulnerability due to the low intrinsic barrier, as well as the sensitivity limitation of volume monitoring by the SMMS due to the high plutonium concentration described in the preceding section, an extraction from the product vessel is the most vulnerable path. Therefore, to investigate further the risk-oriented diversion possibility, a quantitative evaluation has been performed using SANFCE.

In the FBR process, the abrupt diversion is modeled to extract the uranium-plutonium-mixed solution from the product vessel, numbered 20 in Fig. 3(b). The extracted volume is 100L, which corresponds to about 1SQ ( = 8kg-Pu), and is simulated at the operation time scale of 2000 hours, as indicated by an arrow in Fig. 8. The downstream tank level, 21, is lowered by the diversion and is gradually increased by the bypass flow from the crystallization process, 9', as shown in Fig. 3(b). The level in tank 21 reaches a certain level finally. However, the concentrations of uranium and plutonium are apparently decreased by the diversion, and the filled level in the next batch does not reach the maximum level. Because the bypass flow is very dilute and a uranium -enriched solution, the concentrations in tank 21 are not recovered by the supply, even after the volume level is restored. This model is the abrupt diversion, but it is not so easy to detect by the material balance due to the large throughput, over 80 kg of plutonium/day, in the FBR process. However, it can be recognized by the PM algorithm, which has been developed[9] and applied for the tank data.

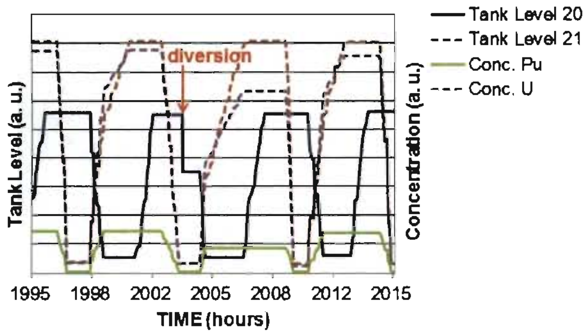


Fig. 8 Abrupt Diversion at Tank 20

As shown in Fig. 9, which presents the real tank data taken from the SMMS in Tokai Reprocessing Plant (TRP), the tank data are composed of a loss of volume sampling at the receiving and shipping times and small ripples so that the tank monitoring software can distinguish the diversion evidence from the meaningless background to construct the DDA. From the statistical decision theory, it should be necessary for a false alarm rate to be determined beforehand based on the baseline derived from the real tank data. Therefore, either the real data from the similar facilities or the preoperational data from the same facility is apparently indispensable.

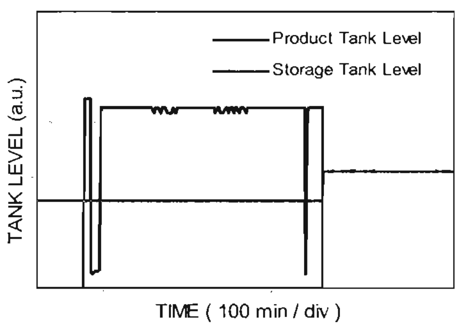


Fig. 9 Real Tank Data from the SMMS in TRP

## V. CONCLUSION

Information-driven safeguards shows a clear tendency toward nuclear power evolution in maintaining a credible and sustainable international safeguards norm. A cost-effective inspection with the maximum use of remote monitoring and a deterrence effect would be the future trend in the IAEA safeguards. In spite of a special case, the bulk-handling facilities, such as large reprocessing and pyro-processing processes, must be safeguarded in a transparent manner to ensure the credibility and objectivity of the IAEA safeguards. The safeguard-ability concept as a strengthened intrinsic feature resulting from SBD has been introduced to enhance an application possibility of process information and monitoring.

However, without showing the theoretical relation between the use of PM and the conventional safeguards criteria based on some formalizations, the conceptual understanding is vague and would be difficult to be installed into the facility design. Therefore, it is very important to unite the safeguards criteria and the PM application in a theoretical way and to make a formal model for the risk-informed quantitative evaluation of the introduction of PM using the S&M approach.

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